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Ventilation control using computational fluid-dynamics (CFD) modelling for cultural buildings conservation

Delia D'Agostino^{a*}, Paolo Maria Congedo^a, Rosella Cataldo^a^aUniversity of Salento, via per Monteroni, Lecce, 73100, Italy

Abstract

The effect of ventilation strategies on the microclimate of the Crypt of Lecce Cathedral (South Italy) was modelled using computational fluid-dynamics (CFD) tools. In the ancient church deterioration mainly consists of efflorescence whose diffusion appeared to be linked to unsuitable indoor conditions.

The model was validated using experimental data collected over a one year microclimatic campaign and allowed to investigate a number of possible ventilation scenarios in the Crypt. The outputs of the CFD simulations helped to establish the ventilation scenario ensuring the microclimate with the lowest gradients and the most appropriate airflows in the building. In the analysis of the results a particular attention was dedicated to the artworks location in order to avoid their decay.

The research allowed to determine how to improve the indoor conditions in the Crypt controlling the ventilation to preserve the monument.

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1. Introduction

It is widely recognized that unsuitable microclimatic conditions can raise the risk of damage especially in ancient monuments where even small microclimate fluctuations can activate processes such as soluble salts crystallization, one of the most diffused deteriorating factors of construction materials [1,2,3,4]. For many chemical compounds, Arnold and Zender [5] reported the critical temperature and relative humidity values that allow destructive phase transitions of ions from dissolved in aqueous solutions to crystallized in salts. In historical collections, above all in hygroscopic and organic works such as wood, ivory, paper and parchment, an increase of relative humidity over

* Corresponding author. Tel.: +39-339-6486865; Fax: +39-0832-665533.

E-mail address: delia.dagostino@unisalento.it.

65% with temperature around 20°C favours biological decay with moulds, bacteria and fungal attacks [6]. Biodecay is also favoured by elevated relative humidity levels as moisture can accelerate the deterioration rate of cellulose in presence of acid or oxidizing agents. Temperature over 24°C can promote chemical deterioration while values slightly above zero can cause thaw damage [7]. When relative humidity is around 20% physical deterioration takes places and, in general, relative humidity changes produce dangerous swelling and shrinking of objects [8]. Moreover, condensation is throughout reported as one of the main causes of paintings and delicate artworks damage [9].

In the last decades microclimatic monitoring has been increasingly cited as a useful tool of improving heritage preservation [10]. However, microclimatic gradients or fluctuations can be missed even with a monitoring program as data recorded in an area can vary in another one, within the same building. Further issues arise as it is hard to monitor continuously many physical parameters. To overcome the question, many modelling tools were developed to predict the parameters that control the indoor environment [11, 12, 13] with the aim of gaining a deeper knowledge of the microclimate or forecasting the consequences of future climate changes [14]. One of the main efforts is to obtain a reliable model and, once achieved, it is a flexible tool that can be combined with experimental data providing significant information on indoor airflow patterns [15].

The reported case study deals with the development of 3 dimensional (3D) CFD models to investigate the thermohygrometric parameters and determine the most appropriate ventilation asset in the context of ancient buildings deterioration. The Crypt of Lecce Cathedral (South Italy) was investigated as unsuitable indoor conditions appeared to be the reason of the efflorescence deterioration.

A CFD code based on the finite element method (FEM) solved all the equations needed to predict the indoor airflow as well as temperature and relative humidity distribution to evaluate both the current microclimatic status and a number of forecast scenarios deriving from a combination of different possible ventilation strategies. Experimental data were used to validate the model and set as boundary conditions to analyze the thermohygrometric parameters in the whole volume of the building with a particular attention to the areas more vulnerable to external factors. The outputs of the simulations allowed to determine how to preserve the monument controlling the indoor ventilation.

2. The case study: the Crypt of Lecce Cathedral

The studied Crypt (40°20'N, 18°07'W) is located in the historical centre of Lecce and it is reachable from the above Cathedral by two stairways (Fig.1). It was built in 1114 by the Normans on a pre-existent underground structure whose function was to guide faithful to meditation and prayer [16].

Until XIX century the Crypt was also used to be a churchyard of priests and nobly born, as showed by the visible tombstones under the floor and into the walls. It is documented that the building underwent a number of changes and renovation works over the centuries: it was reconstructed during the time of the Svevans (1230) and then in the Baroque era, from 1659 to 1670 [17]. The Crypt is actually closed to the public and it can be only accessed to scheduled ceremonies or weddings.



Fig.1: The exterior of Lecce Cathedral and the interior of the Crypt.

Deterioration in the Crypt mainly consists of efflorescence, in the form of white salt crystals covering the walls, columns and the Baroque decorations (Fig. 2). The efflorescence diffusion appeared to be prompted by the indoor microclimate and the outdoor exchange through ventilation. Therefore a CFD model was performed to find the most suitable ventilation scenario for the conservation of the building.

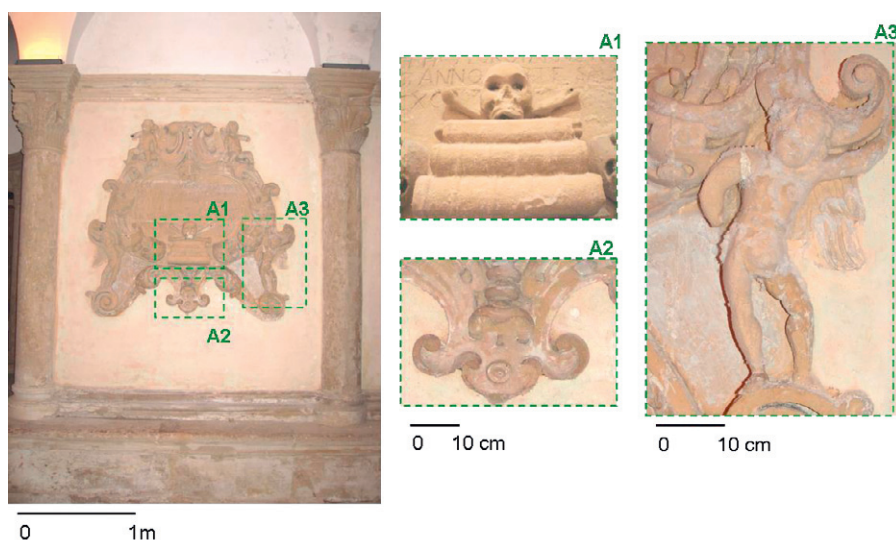


Fig.2: Efflorescence diffusion in the Crypt.

3.Experimental section: CFD model

The CFD model was implemented in the Fluent code v.12.1 [18] based on the finite element method (FEM), to solve the momentum, mass and energy equations. In the study, possible ventilation scenarios corresponding to a combination of different outdoor climatic conditions and airflow inlets were analysed.

The building is in fact linked with the outside through 9 windows (Fig.5) that are currently opened without considering the connected microclimatic effects.

The best ventilation assessment was checked by the CFD simulations considering with attention the areas where most delicate artworks are placed in order to retain here stable airflow patterns.

In this study, 6 main possible opened and/or closed windows scenarios were taken into account together with 2 main wind blows: from North (Fig.3) and South (Fig.4) that lead the air into or out of the Crypt in an opposite way both through the windows and the entrance through which the church communicates with the Cathedral.

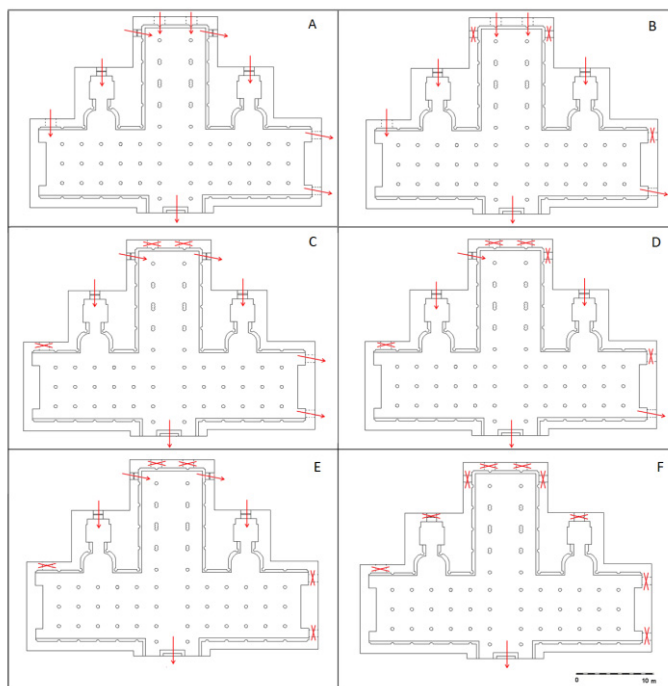


Fig.3: Simulated scenarios (A...F) with North Wind.

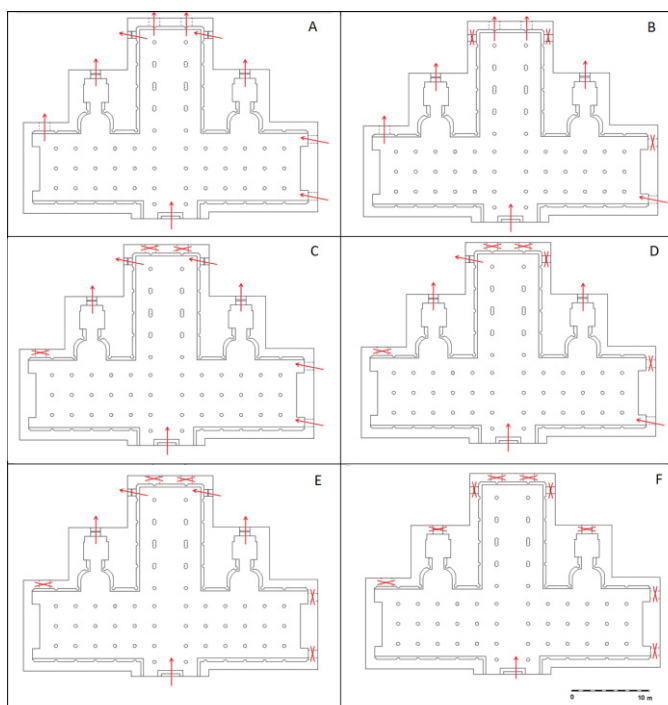


Fig.4: Simulated scenarios (A...F) with South Wind.

Two main seasons (Winter and Summer) were taken into account, for a total of 24 scenarios to be simulated.

The parameters set up in the boundary conditions are reported in Table 1. These experimental data resulted from the climatic and microclimatic instrumentation placed outside and inside the Crypt, considering averaged values for each season. The microclimatic monitoring program was planned to record automatically the main thermo-hygrometrical parameters, including air (T) and surface temperature (Ts), relative humidity (RH), dew point and airflow velocity (v) in the period from April 2009 to April 2010. Sensors (Tinytag Gemini, T: accuracy 0.2°C, resolution 0.4°C, RH: accuracy 3%, resolution 0.5%) were placed inside and outside the Crypt to monitor in a continuous manner air temperature and relative humidity. Indoor measurements were also recorded every 15 seconds using contact temperature probes (Pt100, Ts accuracy $\pm 0.10/0.16^\circ\text{C}$ from 0 to 40°C , resolution 0.01°C), psychrometric probes (Ts: as Pt100, RH: accuracy 3%, resolution 0.1%) and a hot wire anemometer (v: accuracy 0/0.5m/s, resolution 0.1m/s). The probes were connected to the climatic analyser BABUC/LSI (Laboratori di Strumentazione Industriale).

Tab.1: Indoor and outdoor boundary conditions for Summer and Winter (T= temperature, RH= relative humidity, V=velocity, N= North, S = South).

Outdoor	Wind	Winter	Summer
T ($^\circ\text{C}$)	N	11.0	26.1
	S	11.5	28.2
RH (%)	N	81.2	70.2
	S	86.8	76.4
V (m/s)	N	1.8	1.2
	S	2.6	1.6
Flow rate (Kg/s)	N	2.9	1.3
	S	3.4	2.1
Indoor		Winter	Summer
T Walls ($^\circ\text{C}$)		12.1	23.1
T Columns ($^\circ\text{C}$)		12.4	23.3
T Vaults ($^\circ\text{C}$)		13.6	23.7
T Floor ($^\circ\text{C}$)		13.2	22.7
RH indoor (%)		77.1	71.3
T entrance ($^\circ\text{C}$)		16.5	26.4
RH entrance (%)		77.8	73.2
V entrance (m/s)		0.28	0.24
Flow rate (Kg/s)		1.4	0.7

The geometrical 3D model was constructed using Autocad and Gambit software reproducing all the main Crypt components. The full scale geometrical CFD model contains an air volume of 1880 m^3 that was approximately divided into 7.500.000 tetrahedral cells, each representing about a $10\times 10\times 10\text{ cm}^3$ volume, obtaining an independent grid model.

The model was validated comparing the outputs of the CFD simulations with the experimental data obtained in specific surveys using an electronic psycometer (TECNOEL, accuracy 0.1°C, resolution 0.01°C). Data were analysed on 27 plans on X,Y,Z axis across the Crypt at 3 different heights from the floor (Z = 1, 2, 3 m) with 2m space (Fig.5).

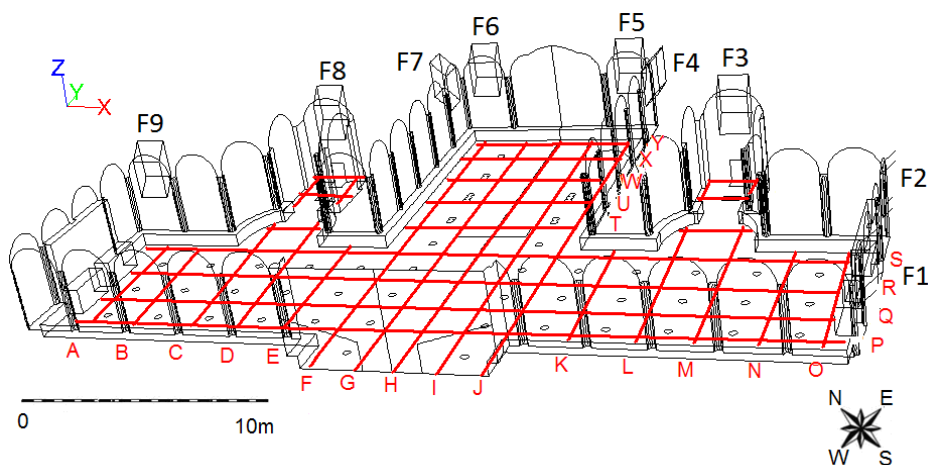


Fig. 5: X and Y plans for model validation and results visualization. Crypt's windows denomination (F1...F9) is also reported.

Table 2: Comparison of average measured and simulated data (plan Z= 1m).

PLAN	T MEASURED (°C)	T SIMULATED (°C)	RELATIVE DIFFERRECE	RH MEASURED (%)	RH SIMULATED (%)	RELATIVE DIFFERRECE
X = A	13.83	14.07	1.73%	74.30	77.73	4.61%
X = C	13.64	13.73	0.65%	76.50	78.42	2.50%
X = E	13.50	13.68	1.33%	76.50	79.39	3.77%
X = G	13.75	13.69	0.43%	76.10	78.06	2.57%
X = I	13.80	13.83	0.21%	76.10	77.88	2.34%
X = M	13.70	13.93	1.67%	75.80	78.48	3.53%
X = O	13.60	13.82	1.61%	77.10	78.90	2.33%
X = Q	13.57	13.77	1.47%	76.00	79.03	3.98%
Y= B	13.62	13.65	0.22%	76.30	79.24	3.85%
Y= D	13.58	13.71	0.95%	76.50	79.39	3.77%
Y= F	13.50	13.65	1.11%	77.30	78.90	2.06%
Y= H	13.50	13.72	1.62%	77.30	79.39	2.70%

Table 2 reports the relative difference between measured and simulated air parameters for some of the analysed plans. These values satisfied the validation criteria that allowed below 2% for temperature and 5% for relative humidity. In particular, air temperature predicted by the model appeared very close to the measurements with relative difference below 1.73%.

4. Results: CFD outputs

The convergence was reached after about 1500 iterations obtaining residuals under 10^{-6} . The outputs of the CFD simulations were analyzed on the X, Y, Z plans of Fig. 5 where the distribution of the thermohygrometric parameters was visualized for the scenarios.

A particular attention was given to the airflow patterns and to the localization of the microclimatic gradients. The Scenario A produced an indoor microclimate too influenced by the outdoor conditions. It showed an indoor increase of the average temperature of 16.8°C with variations over 30% for relative humidity when the climatic conditions changes from Summer to Winter. A maximum gradient of 6.2°C temperature and 43% relative humidity was obtained when wind changed from North to South (air velocity between 0.4 and 0.6 m/s).

The Scenario B was also considered unsuitable for artworks conservation. It showed average seasonal gradients of 14.3°C temperature and 29% relative humidity. However, a lower variability was found between North and South wind within the same season, especially in Winter conditions when an average variation of 0.4°C temperature and 3% relative humidity was shown with a maximum fluctuation of 1.2°C and 4% respectively.

Scenario C gave temperature values in the range between 12.1°C and 15.7°C in Winter and 19.6°C and 27.2°C in Summer with relative humidity between 64% e 86% in the both seasons. A small range of temperature and relative humidity values were determined in the Winter conditions, especially with North wind. Most fluctuations appeared with South wind, when air entered through F1, F2 and F4. Although gradients appeared lower in this scenario, simulations showed an important airflow in the area of the right Baroque altar. Particularly, with South wind, when air went into the Crypt by the windows F1 and F2, airflow pattern appeared intense in correspondence of the damaged fresco, contributing to its decay.

Results showed how Scenario D gave more suitable temperature and relative humidity conditions with an average temperature of 22°C (North wind) and 22.5°C (South wind) in Summer and 14.2°C (North wind) and 14.6°C (South wind) in Winter. The same values for relative humidity were 64% (North wind) and 70% (South wind) in Summer and 72% (North wind) and 76% (South wind) in Winter. Fluctuations were lower compared to the previous cases, being equal to 2.8°C in Summer and 2.4°C in Winter and for relative humidity 14% in Summer and 18% in Winter. However, also this scenario was not suitable for canvas conservation as window F1 generates turbulence near the Baroque altar in the right aisle. Therefore, F1 and F2 windows should always be kept close.

The scenarios giving most suitable microclimatic values were those of Scenario E and F as they assure suitable temperature and relative humidity values within and between the seasons. Moreover, indoor conditions are not affected by wind changes, and a low airflow creates lower turbulence and small variations of temperature and relative humidity.

Scenario E showed temperature between 19.2°C and 23.0°C in Summer (average 21.4°C) and between 15.9°C and 18.9°C in Winter (average 17.7°C). Relative humidity was between 48% and 70% in Summer (average 60%) and between 53% and 75% in Winter (average 65%).

The Scenario E seems to be preferable when the Crypt is opened to the public as it provides a better air replacement, useful to avoid problems related to the presence of visitors (Fig.6).

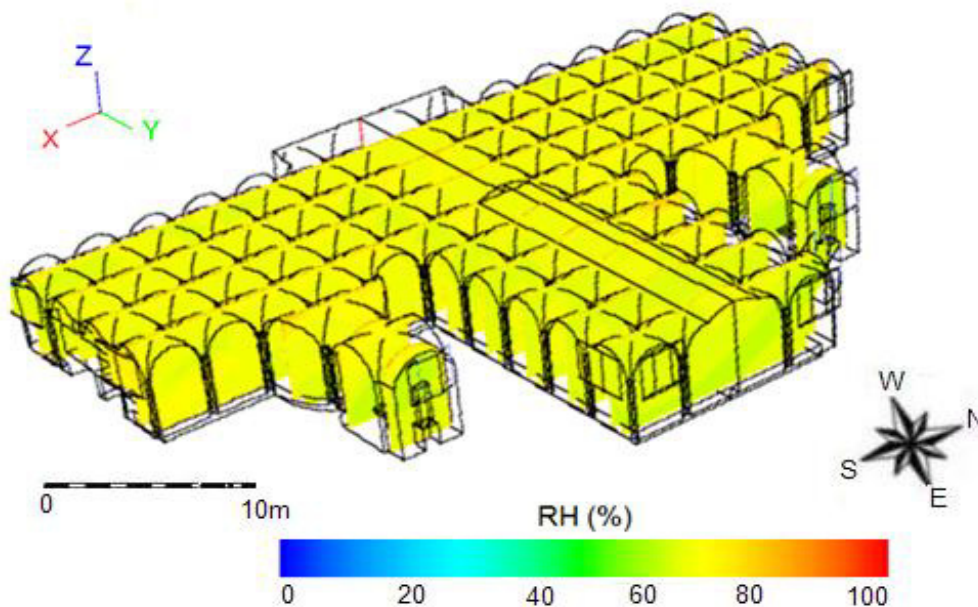


Fig.6: Scenario E: Relative humidity distribution on Y plans in Summer conditions with South wind.

Considering that the Crypt is actually closed to the public and that people comfort is secondary in respect to conservation needs, the scenario ensuring the lowest microclimatic gradients and fluctuations is the Scenario F that permits airflow only by the entrance.

This assessment ensures stable indoor relative humidity in the range between 45% and 67% with a gradient of 13% within Summer and 17% within Winter. Temperature range was between 15.6°C and 22.5°C in the whole period with a 3.1°C gradient during Summer and 4.8°C in Winter (Fig.7). Temperature never falls under 15.6°C in Winter and never rises up to 22.5°C in Summer with a minimum relative humidity of 45% and a maximum of 67%. When season changes, simulations showed a variation of the average temperature of 3.2 °C and of relative humidity of 6% with a maximum difference of 6.9 °C temperature and 22% relative humidity. As regards the airflow, it was the lowest in Scenario F compared to the other scenarios, between 0.10 m/s and 0.15 m/s. These values are suggested by the conservation science and assure stability in the most delicate areas of the Crypt.

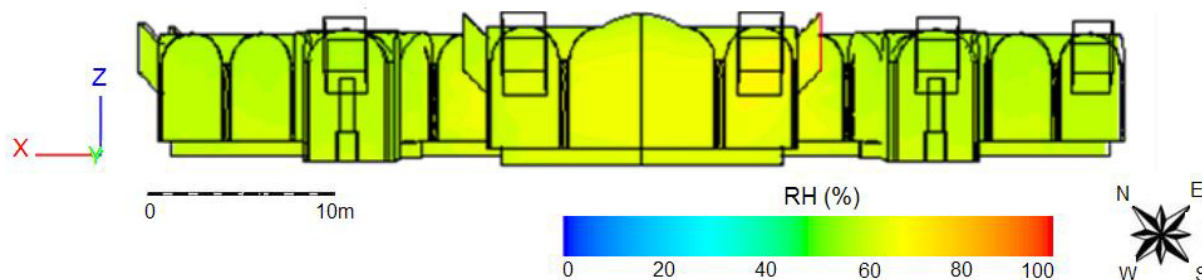


Fig.7: Scenario F: relative humidity distribution on Y= S plan in Winter conditions with North wind.

5. Conclusions

The paper illustrated that CFD models can contribute to have a better control of the indoor environment in cultural buildings. CFD simulations showed how the model could predict temperature, humidity distribution and air movement change in response of the opening or the closing of different airflow inlets.

Considering the results, the following main actions for improving the Crypt's conservation can be synthesized:

- Crypt's windows should never be opened at the same time as this cause a microclimate too much influenced by the outdoor variations;
- to retain a temperature and consistent humidity throughout the Crypt, all the windows should be kept close. This also limits the airflow and the turbulence near the walls and columns, reducing evaporation from the masonry and also the efflorescence formation;
- in case of people presence, the windows to be opened should be F3, F7, F9, while F1 and F2 should always be kept close for artworks conservation. In this case, a double glass installation could limit the direct contact with the external climate.

The paper confirms that CFD modelling supported by microclimatic monitoring is a powerful tool in cultural building monitoring and management.

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